

# STUDY ON STRENGTHENING OF DAMAGED REINFORCED CONCRETE COLUMNS WITH GEOPOLYMER JACKETS

GABBETA SWATHI\*, DR.L.SAI INDRASENA REDDY\*\*

PG SCHOLAR\*, ASSOCIATE PROFESSOR\*\*

MOTHER TERESA INSTITUTE OF SCIENCE AND TECHNOLOGY, SANKETIKA NAGAR, KOTHURU, SATHUPALLY, TELANGANA 507303

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**ABSTRACT** The objective of this investigation is to experimentally study the behaviour of reinforced concrete (RC) columns strengthened using RC and geopolymer concrete (GPC) jacketing by subjecting them to axial loading. The experimental results were analytically validated by the finite element model (FEM). For this investigation, six columns of M25-grade conventional concrete were subjected to more than 75% of the ultimate load. Then three columns were jacketed by using M40-grade RC and another three columns were jacketed by using M40-grade GPC. The interfacial behaviour of the conventional RC column and jacketed GPC columns was studied and compared. The 3D linear and FEM was employed to measure the effect of conventional RC and GPC-jacketed columns under increasing load by considering the concrete damage plasticity (CDP) and elastoplastic models with isotropic hardening. The validation against the experimental results confirmed 90% accuracy of the analytical model

**1. INTRODUCTION** Reinforced concrete structures undergo deterioration in a variety of ways due to wetting and drying cycles, freezing and thawing cycles, corrosion, chloride attack, tidal zones and other physical/- chemical causes. Therefore, there is a need to improvise the existing structures to meet the precise design requirements. Structural repair and strengthening of the structures have received worldwide attention [1,2]. Depending upon the type of distress, the techniques applied for the repair of damaged structures vary [3]. Some of the methods extensively used for strengthening of reinforced cement concrete (RCC) structures are patch repair, shotcrete, internal or external prestressing, jacketing by concrete

and steel and externally bonded fibre-reinforced plastic (FRP) reinforcement [4]. Maintenance and repair work is estimated to account for about 85 % of the total expenditure in construction worldwide and there is always an increased need for upgrading the existing infrastructure to meet stern design necessities. Therefore, structural repair and strengthening have received considerable attention from researchers [5]. The premature deterioration of reinforced concrete structural members leads to the most critical problems in civil infrastructure. Reinforced concrete elements require repairs or strengthening when service loading causes excessive deflections and cracking. There is a necessity to enhance the service life of the RC element and incorporate the changes of design parameters to satisfy the stringent limits on serviceability and ultimate strength in accordance with the current codes. The replacement of such deficient structural members requires a huge amount of materials produced from natural resources, which is not environmentally feasible. Also, buildings of historical importance need to be preserved. In these cases, it becomes essential to strengthen the existing structural member depending on the type of construction and the condition of damage [6]. Concrete jacketing is a method for retrofitting or rehabilitation of RC structures damaged seismically or due to poor construction. In this method, a concrete and steel reinforcement is added to an existing column or beam [7]. Depending on the location and environmental conditions, suitable materials should be chosen for retrofitting to ensure the lasting performance of the structure after repair. Therefore, material selection and jacketing design play a major role [8]. The need for new materials with enhanced properties, which can provide higher performance, is imperative now than ever before in construction. The materials used to produce concrete structures should have four distinctive properties such as strength, workability, durability and affordability. To address the problem of the rapid deterioration of infrastructure and massive utilisation of construction materials (that consume natural resources), alternate materials have emerged, which include self-compacting concrete, engineered cementitious composite, fibre-reinforced concrete, reactive powder concrete, lightweight concrete, high-ductile fibre-reinforced concrete, geopolymer concrete and ultrahighperformance fibre-reinforced concrete [3]. Concrete is the most ubiquitous material used for construction worldwide. It is a heterogeneous mixture consisting of cement, water, aggregate and air. Concrete consumption has been estimated to be one meter cube per person per year [9]. The manufacture of ordinary Portland cement (OPC) is known to cause heavy CO<sub>2</sub> emission [10]. So, environmentally friendly alternatives are being explored. One alternative is the substitution of OPC by a geopolymer concrete (GPC), which is produced

from fly ash (a fine powder waste taken from the emissions of coal-burning power stations) and groundgranulated blast furnace slag (GGBS) (a powder waste product of iron and steel-making that is activated by an alkaline activator or reaction-generating liquid). This binder lowers carbon emissions when compared to OPC concrete [11]. It was noted that GPC possesses very high strengths and does not require conventional water curing like the Portland cement-based conventional concretes. GPC can set and harden at room temperature and can gain reasonable strength within a short period [12]. GPC thus led to the development of cost-effective, environmental friendly and innovative material for construction. This sustainable construction material has been used in a large number of applications, thereby contributing to an improved quality of life for humankind. The advantage of strengthening a structure using RC jacketing over the steel bracing method is the uniform distribution of increased strength and stiffness of the column, in addition to fortification against corrosion and fire. Also, this strengthening technique does not require any specialist skills. All these factors make RC jacketing a tremendously valued choice in structural rehabilitation [13]. The rehabilitation of the deteriorated RC column is increasing due to the need for maintenance and severe exposure conditions. Hence the studies related to rehabilitation need to be undertaken to circumvent the social costs related to the demolition and reconstruction of new structures. As of now, there is no clarity on the interface behaviour of concrete jacketing. The high-performance materials such as ECC, FRP and UHPC in the applications of retrofitting of bridge columns [14], RC columns under cyclic loading [15], jacketing of RC columns using ECC [16], repairing of RC columns using FRC [17], strengthening of RC columns using high-performance FRC [18] and RC columns using CFRP [19] are widely employed in construction. The novelty of the present work is the analysis of the jacketing of low-grade RC column with high-grade concrete and GPC concrete using an analytical model based on FEA software and comparing the output with experimental test results.

**EXPERIMENTAL PROGRAM** The experimental program consists of testing one-third scale square (150 150 mm) column specimens with a height of 1000 mm in three phases as follows; Phase 1: Control column specimens without any preloading and without ferrocement jackets, Phase 2: Jacketed column specimens without any preloading but with ferrocement jackets, and Phase 3: Strengthened preloaded column specimens include columns strengthened with ferrocement jackets after preloading them with 60%, 80% and 100% of their ultimate axial strength. The number and details of the square reinforced concrete column specimens are given in Table 1. The details of reinforcements and dimensions of the square

reinforced concrete column specimens are shown in Fig. 1. The ferrocement jacket used in the experimental program was the same for all column specimens and consisted of two layers of WWM wrapped around the column and encapsulated in high strength mortar. The two layers of WWM were chosen for all specimens because it was found to be reasonably managed and handled during wrapping according to the available facilities in the lab.

**Materials properties** The materials used in preparing the concrete mix include ordinary Portland cement (ASTM Type I), crushed limestone coarse aggregate with a maximum size of 10 mm, an absorption capacity of 1.5%, and an oven dry bulk specific gravity of 2.60, a mixture of washed sand and natural silica sand with an absorption capacity of 1.5% and 0.1% and an oven dry bulk specific gravity of 2.56 and 2.52 respectively, and tap water. The concrete mix used consists of 300 kg/m<sup>3</sup> Portland cement, 700 kg/m<sup>3</sup> crushed limestone, 600 kg/m<sup>3</sup> washed sand, 450 kg/m<sup>3</sup> silica sand, and 195 kg/m<sup>3</sup> free water. The concrete mix was designed in order to obtain a target cylindrical compressive strength of 25 MPa after 28 days. It was intended to use and investigate the effectiveness of using ordinary locally available WWM as a low cost material in rehabilitation and upgrading reinforced concrete columns. The WWM used in the jackets had square openings of (12 12 mm) and wire diameter of 0.94 mm. Tensile tests were performed on three coupons and the wire yield strength was determined in accordance to ACI committee 549, 1988 [17]. The average yield strength was 385 MPa at a yield strain of 0.0037, and the average ultimate tensile strength was 524 MPa, while the average modulus of elasticity was 106 MPa. Different mixes of mortar were designed and prepared in order to develop high strength and flowable mortar [18]. The materials used in preparing mortar specimens include locally available ordinary Portland cement (ASTM Type I) with a specific gravity of 3.15, natural silica sand with a specific gravity of 2.60 and a fineness modulus of 1.65, silica fume and fly ash were in powder form with a specific gravity of 2.2 and 2.3 respectively. Superplasticizer of a melamine formaldehyde sulfonated superplasticizer type with a specific gravity of 1.21 was incorporated in all mixes to maintain the same degree of workability. The mortar mix proportions were 1:2:0.15:0.05:0.4:0.04 by weight of type I cement, silica sand, silica fume, fly ash, water and superplasticizer, respectively. The mortar mix achieved a compressive strength of 63 MPa and tensile strength of 5 MPa after 28 days and a flow of 132%.

**Preparation of specimens** Preparation of column specimens The longitudinal reinforcement and stirrups were previously prepared before placing it in horizontal wooden molds that were specially made for the square column specimens. One strain gage was attached at the middle

of each of the two diagonally longitudinal reinforcement bars of each column. The readings of those strain gages were used at the initial stage of the test to adjust the specimen in the testing machine to ensure perfect verticality with minimal eccentricity during testing by obtaining equal readings in those strain gages. In addition, two strain gages were attached to the middle stirrup of the column to determine the lateral strains in the stirrups and to compare its readings with those pasted on the concrete surface. The prepared steel cage was carefully placed in the wooden mold after oiling its surface so that it was spaced from the sides of the molds by 13 mm using wooden spacers at edges, which is considered to be the concrete cover. The molds with the steel cages were placed on the vibration table at a low speed while the concrete was poured. After casting, the specimens were covered with wet burlap in the laboratory at 23 C and 65% relative humidity. The specimens were demolded after 2 days and wrapped with damp cloth for 14 days. The control and preloaded column specimens were prepared for testing after 28 days from casting. While other column specimens were tested after applying the ferrocement jackets.

**Preparation of ferrocement jackets** The ferrocement jackets were prepared using two layers of Welded Wire Meshes (WWM) and covered with a flowable high strength mortar jacket using specially designed molds. The ferrocement jackets were applied to the unloaded column specimens after 28 days from the day of casting. While the ferrocement jackets were applied to the preloaded and failed columns after being tested to 60%, 80% and 100% of their axial capacity. Before applying the ferrocement jackets all column specimens were sand-blasted to roughen their surfaces for a better bond between the concrete surface and the applied mortar layer. Two horizontal strain gages were placed at the two opposite sides of the concrete column at its mid height, in order to determine the lateral strains at the concrete surface. The process of wrapping the WWM around the specimen includes attaching the edge of the mesh to the surface of the specimen using a high adhesive bonding paste known as Sikadur-31, and then wrapping the two layers of WWM around the column specimen. The joints of the mesh were secured at different locations together using double thin steel wires that are commonly used in tying reinforcing bars. To maintain the integrity of the WWM layers and to increase its attachment to the plain concrete specimens, the bonding paste of Sikadur31 was applied at four spots along the height and clamped to the specimen until it hardened

**CONCLUSIONS** Based on the test results of this investigation the following conclusions can be drawn:

1. Ferrocement jackets have been utilized as an alternative repair/strengthening technique for increasing the axial load carrying capacity and ductility of tied reinforced concrete columns. The investigation was limited to ferrocement jackets containing two layers of ordinary Welded Wire Meshes (WWM) encapsulated with 20 mm high strength ferrocement mortar. The limitation in number of layers was due to matters related to managing and handling the WWM during wrapping the specimens.
2. Test results indicated that strengthening unloaded reinforced concrete columns of 150 150 mm square cross section and a height of 1000 mm, with two layers of WWM ferrocement jackets showed about 33% and 26% increase in axial load carrying capacity and stiffness respectively, compared to control columns.
3. Test results indicated that repairing similar reinforced concrete columns of square cross section preloaded up to 60% and 80% of their ultimate load carrying capacity, with the same jackets showed about 28% and 15% increase in axial load carrying capacity as compared to control columns.
4. Test results indicated that repairing similar reinforced concrete columns of square cross section preloaded up to failure with the same jacket restored almost the original load carrying capacity and stiffness of control columns.
5. The strengthened and repaired columns failed in a ductile manner characterized by the larger area enclosed by the load displacement curve at the end of the test compared to a brittle failure in case of control columns. However, the repaired failed columns showed a significant loss in ductility due to the existence of cracks in failed columns.

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